Enabling High Performance Instruments for UV Astronomy and Space Exploration with ALD

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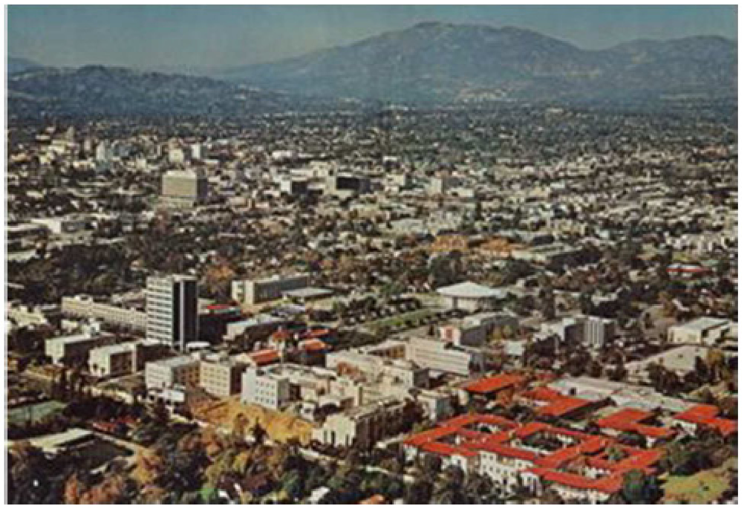
Outline

- Introduction to Jet Propulsion Laboratory
- Overview of Applications and Results
  – Anti-reflective coatings
  – Optical elements (mirrors/filters)
  – Surface treatments and passivation
- Conclusions and acknowledgements

Jet Propulsion Laboratory



• JPL is a child of Caltech: founded in 1936 as a graduate student project under Professor Theodore von Kármán.

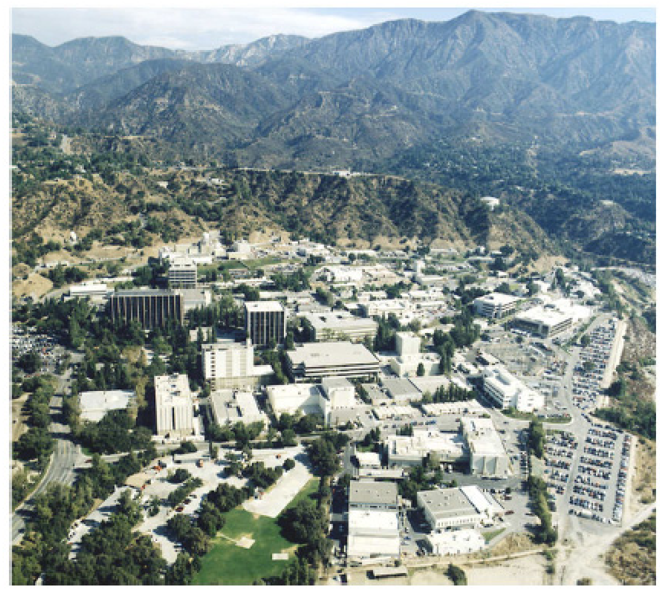
• JPL led the development of US rocket technology in WWII.

• Developed the first U.S. satellite, Explorer I.

• JPL was transferred to NASA upon its creation in 1958.

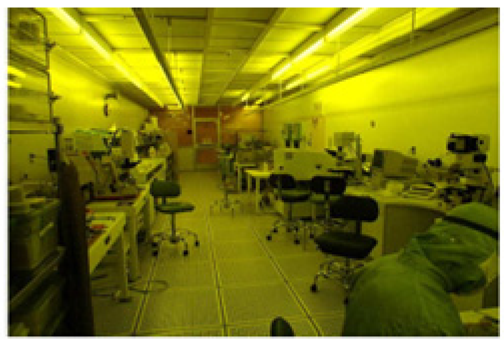
• JPL spacecraft have explored all the planets of the solar system except Pluto.

- About JPL:
  - A Federally-Funded Research and Development Center (FFRDC) under NASA sponsorship;
  - A division of Caltech, staffed with > 5000 Caltech employees;
  - JPL Director is a Vice-President of Caltech.
- Programs:
  - NASA programs;
  - Defense programs and civilian programs of national importance compatible with JPL capabilities.



Microdevices Laboratory

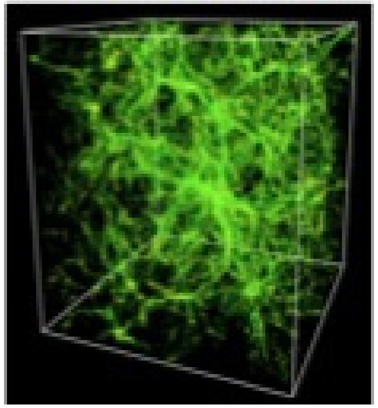
- MDL Facility built in 1989 to provide end-to-end capabilities for advanced electronic materials, device fabrication and characterization.
- Class 10–1,000 cleanrooms with e-beam & optical lithography, materials growth & deposition, wet & dry etching, thermal processing, optical/structural/electronic characterization capabilities for detector devices.
- Nom. $ 30M of equipment investments are housed within MDL with 74 major pieces of Central Processing Equipment.
- Chartered to carry out innovative research and technology development for NASA applications and deliver instruments and components to flight applications
- Recent deliveries include superconducting detectors for the Herschel SPIRE and the Planck High Frequency Instrument that was launched by ESA in 2009



Applications of UV Detectors

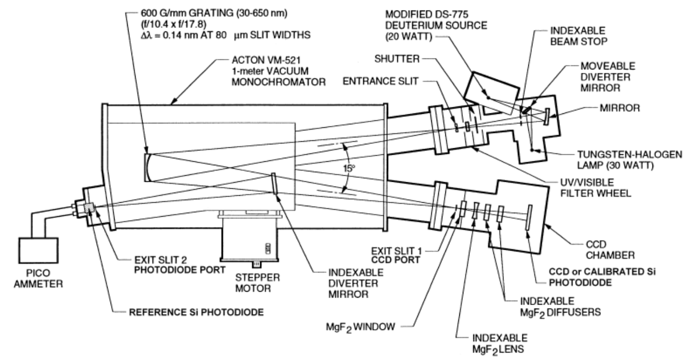
- Spectroscopy to investigate planetary atmospheres
  - Detection of Ozone (biomarker)
- Imaging and Spectroscopy for Astronomy and Cosmology
  - *e.g.* Galaxy Evolution Explorer (GALEX)
  - Star formation/Dark Energy studies
- Imaging for biomedical applications, Criminal investigations, and defense
  - Tumors
  - Bite marks/bruises
  - Rocket plumes

Illustration of GALEX and a proposed map of intergalactic medium



CCD Characterization

- Characterization of absolute quantum efficiency of detectors is very difficult in the UV
  - Atmospheric absorption occurs in wavelengths < 160nm
  - Silicon CCDs must be cooled to liquid nitrogen temperatures to reduce dark current
  - Quantum yield (electrons/photon) is greater that 1 for short wavelengths
- JPL has developed a system and methodology for these tests in our laboratory for rapid feedback during detector development and flight qualification*



*B.C. Jacquot, S.P. Monacos, M.E. Hoenk, **F. Greer**, T.J. Jones, and S. Nikzad**,** *Rev Sci. Inst.* 2011

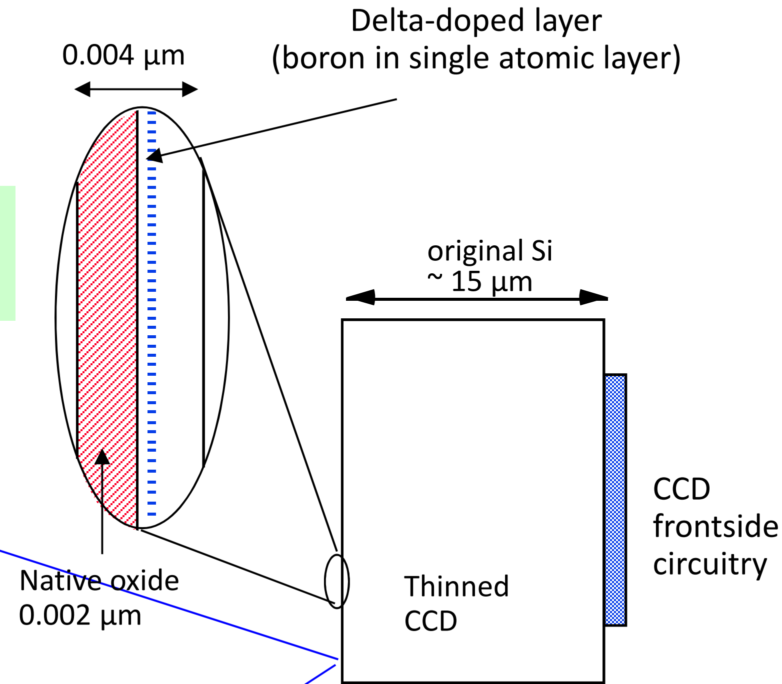
Delta doping technology as the ideal Back Illumination solution

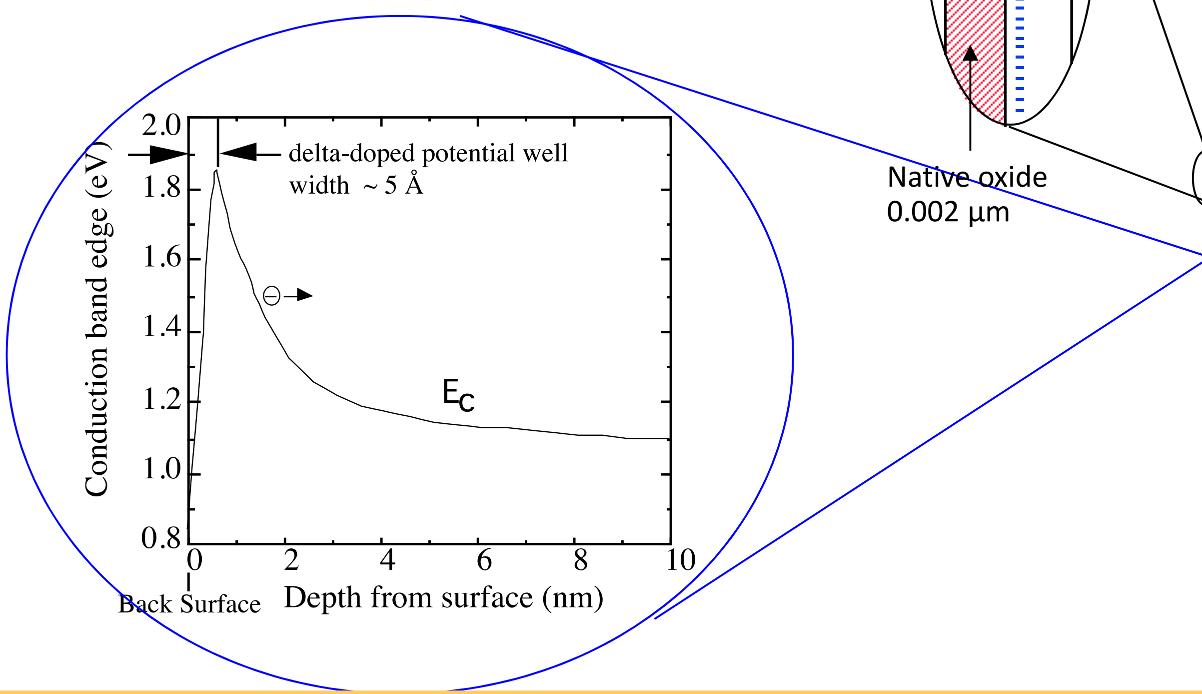
Bandstructure engineering for optimum performance

Atomic layer control over device structure

Low temperature process, compatible with VLSI, fully fabricated devices (CCDs, CMOS, PIN arrays)

Hoenk et al., *Applied Physics Letters*, **61**: 1084 (1992)

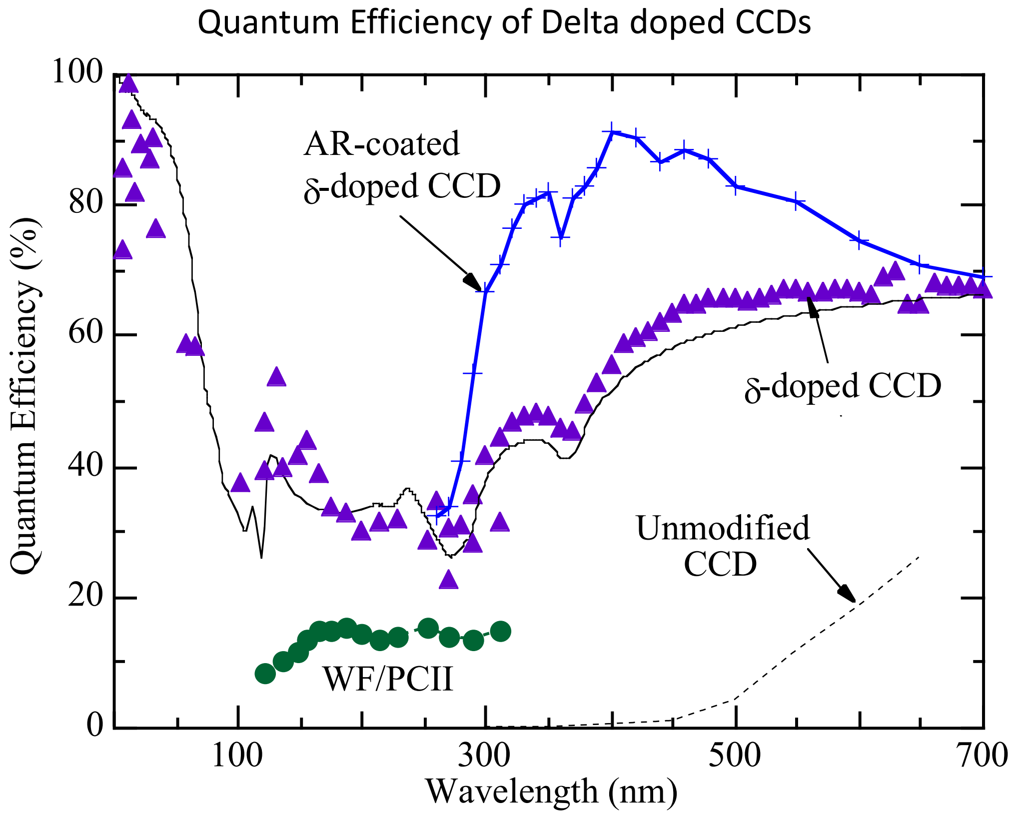




Fully-processed devices are modified using Molecular Beam Epitaxy (MBE)

S. Nikzad, 2011

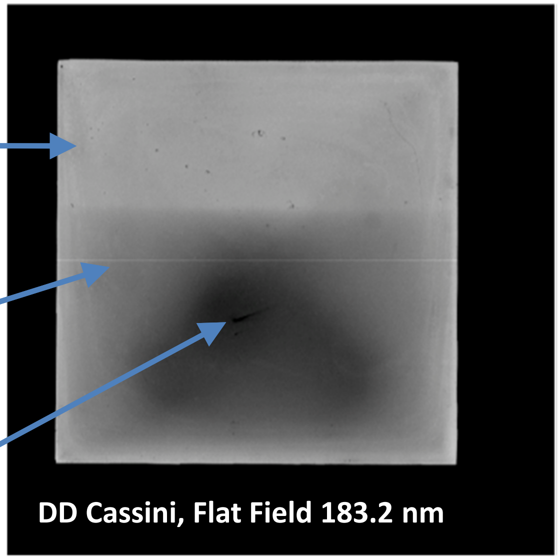
High QE with Delta doping Technology

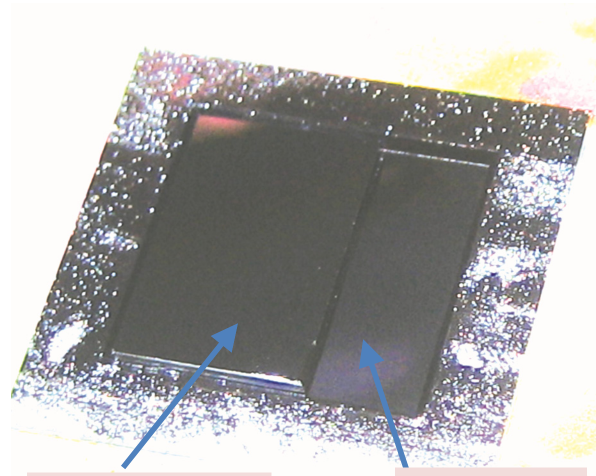


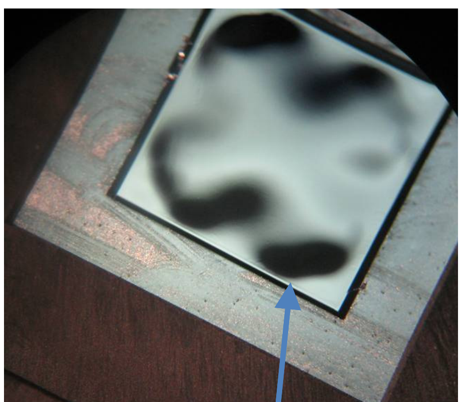
- 100% internal quantum efficiency, uniform, and stable (QY has been removed so maximum QE is 100%).
- Extreme UV measurements were made at SSRL
- Compatible with AR and filter coating: response can be tailored for different regions of the spectrum

S. Nikzad, 2011

Anti-Reflective Coatings for UV Astronomy

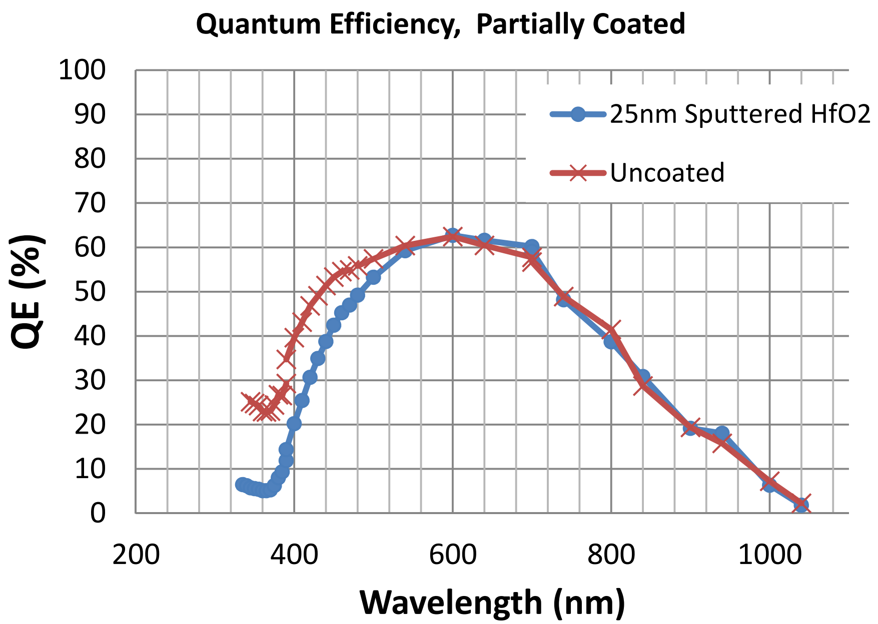


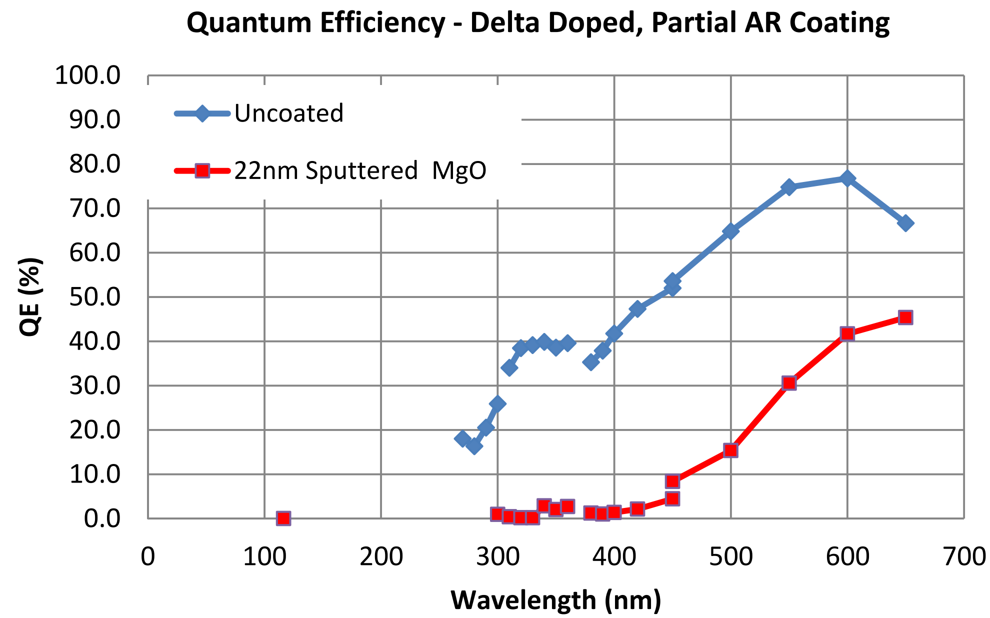




- AR Coatings used to enhance quantum efficiency of silicon detectors.
    - Many different materials needed for UV detection due to adsorption
    - Brighter → Higher QE
- Shadow masking used to ensure internal standard for comparison
    - Shadow masking is somewhat difficult due to conformality of the ALD coating process
    - Mask does not sit flat on unsupported membrane

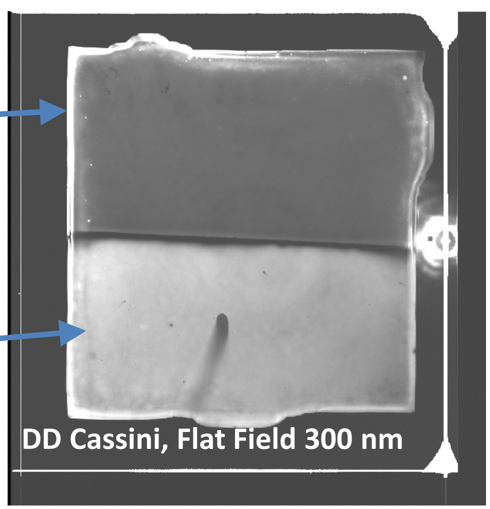
Sputtered anti-reflective coatings





Sputtered AR coating

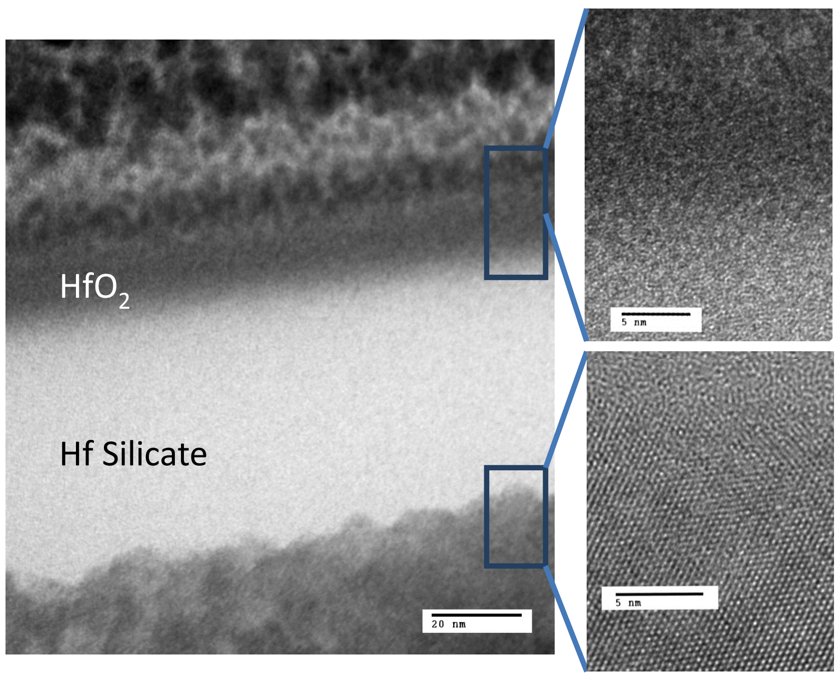
Masked NO AR coat



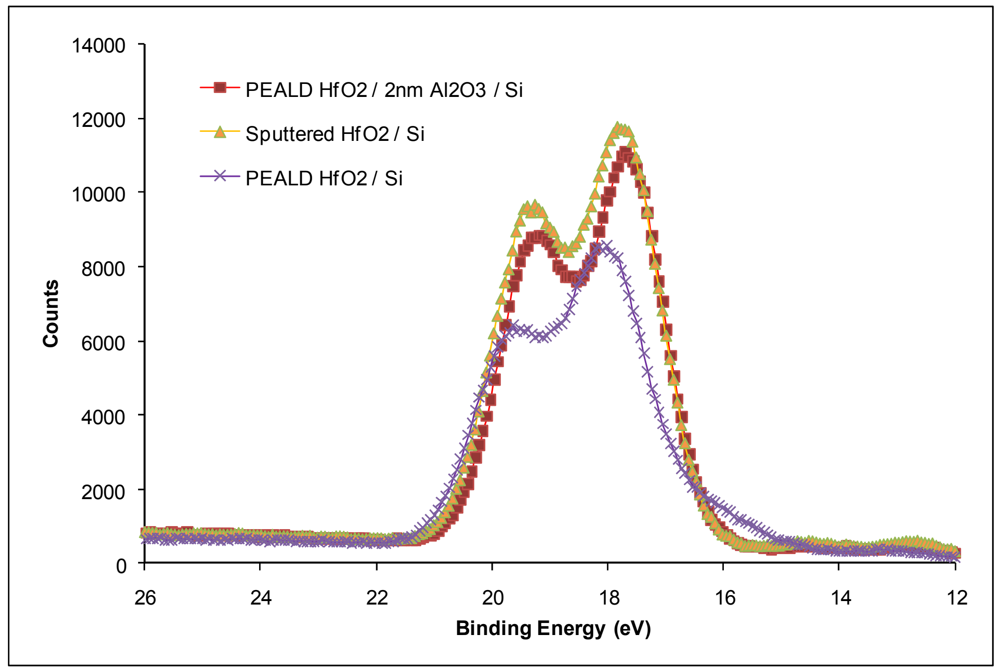
- Atomic Layer Deposition yields ***superior AR coating performance compared to sputtered films***
  - Sputtered film QE far below that of uncoated reference
  - Various materials analysis techniques used to investigate this result

Importance of Chemistry in ALD AR Coatings

TEM of PEALD HfO_2 directly on Si

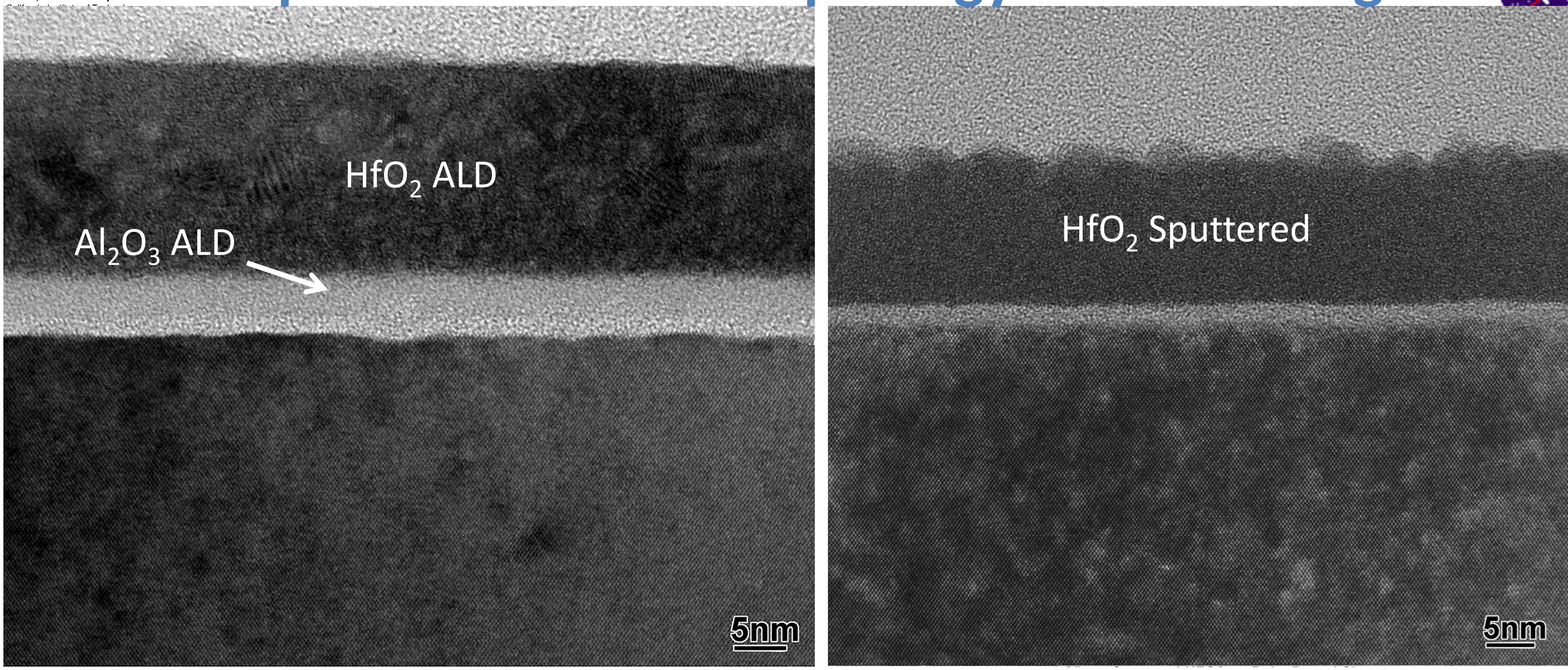


XPS Data from initial AR coating growth



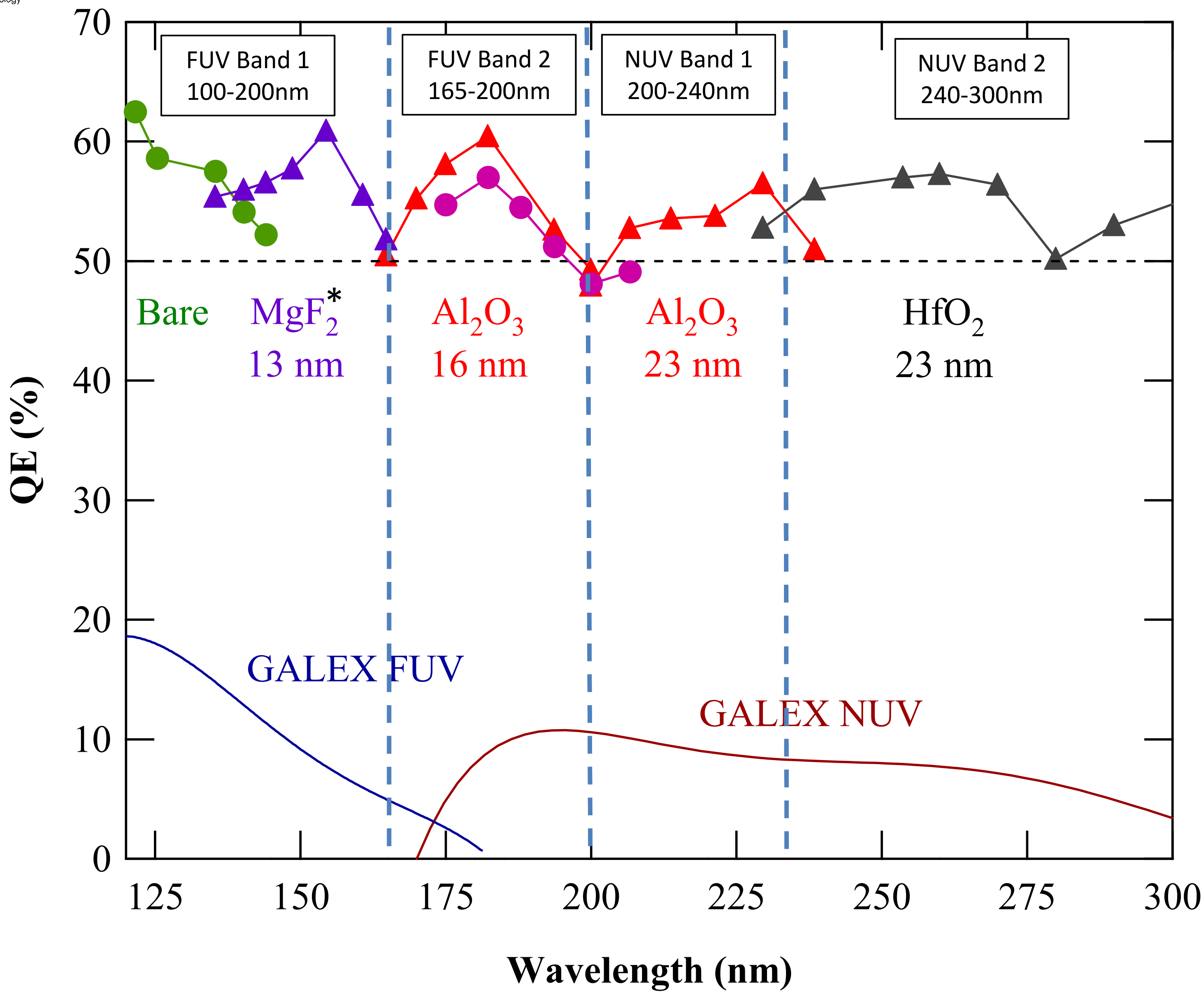
- Chemical interaction of ALD coating with substrate is possible.
- ALD bilayers were utilized to successfully mitigate this effect

Comparison of Nanomorphology of AR Coatings



- ALD AR coating Stack (Left) is significantly better than the Sputtered AR coating (right)
  - ALD is more dense (darker in the image)
  - ALD is smoother (potentially less scatter)
  - ALD is partially crystalline
- ALD AR coating technique allows for multilayers with sharp interfaces
  - Provides for optically transparent chemical barriers between films (Al2O3 film at left)
  - Can create band pass filters or AR coatings that are highly tailored to a specific wavelength
- ALD AR coating technique has atomic layer precision
  - Enables sub-nanometer control over film thickness, which is important for UV AR coatings as <2nm thickness change impacts the performance

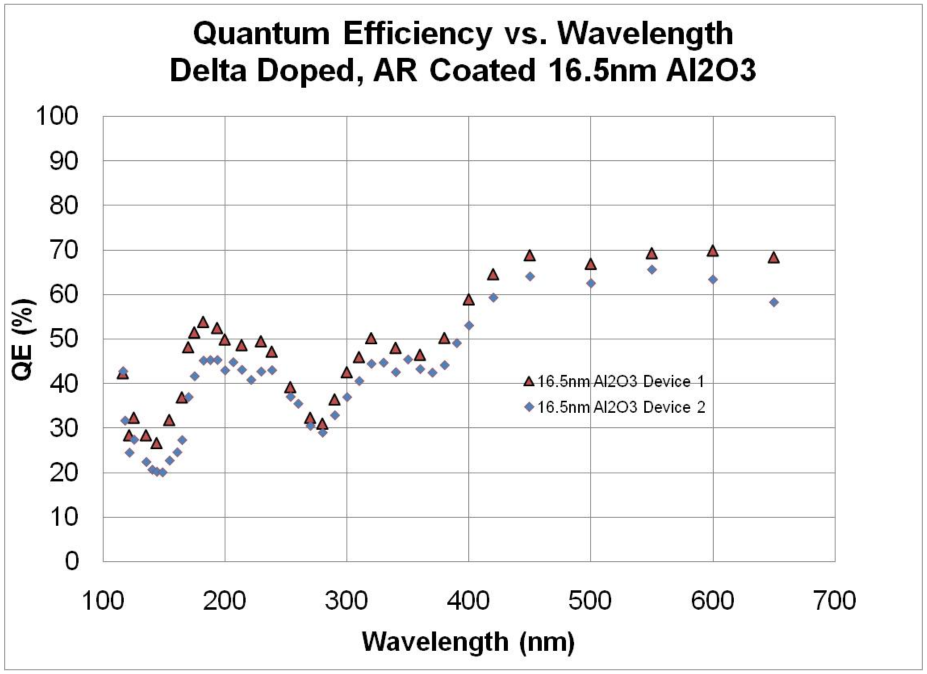
Quantum Efficiency of FUV-NUV Bands



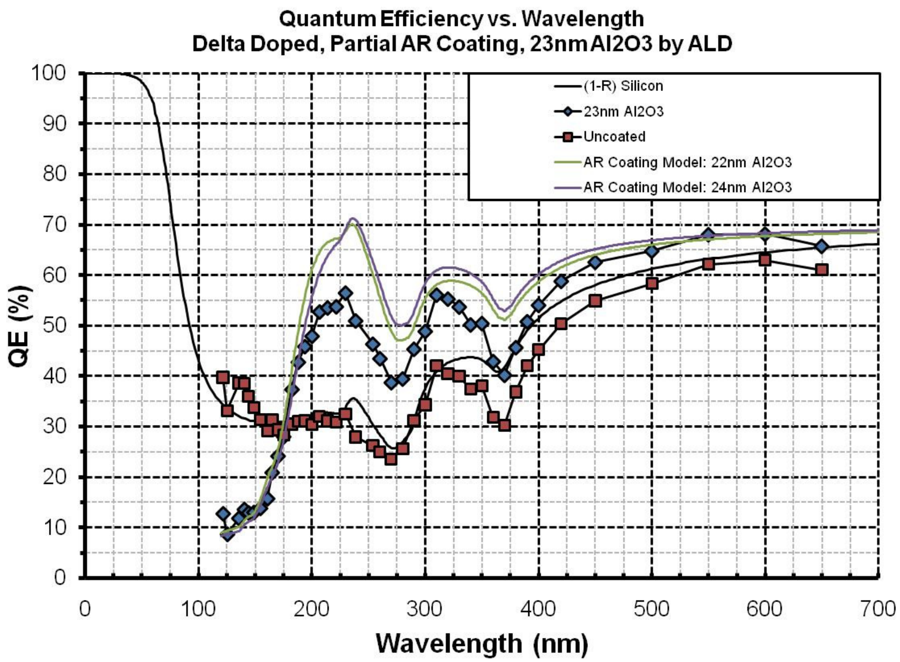
*MgF_2 result for thermally evaporated film

Atomic Layer Deposition AR coatings provide up to ***2X improvement*** over uncoated baseline and a ***5x-50x improvement*** over incumbent UV detector technology

ALD Enables Atomic Control of Coatings



Same exact recipe run on JPL ALD system on two different devices separated by ***a month***

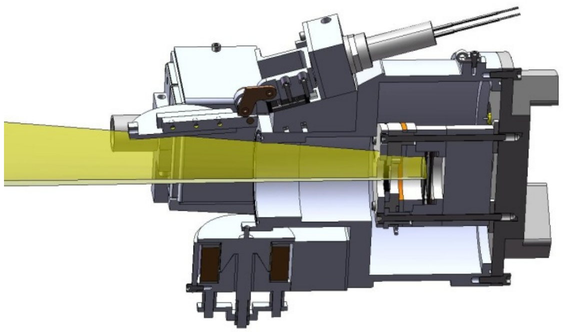


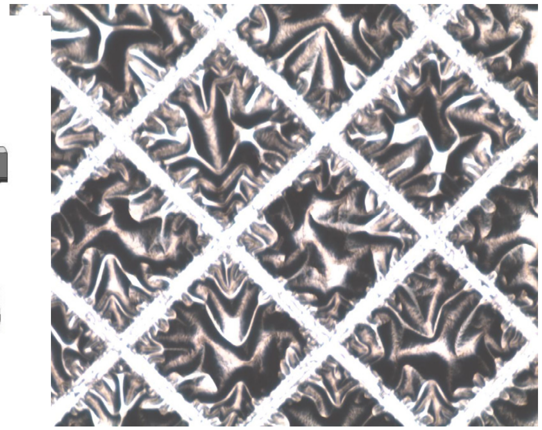
Wavelength dependence of coating performance ***correctly predicted*** by AR coating models based on precision UV ellipsometry measurements

- Reproducibility and accuracy of the ALD technique enables rational design and fabrication of anti-reflective coatings at the nanometer scale
- Multilayers feasible when required to prevent interactions or to provide for integrated filters (*e.g.* bandpass)

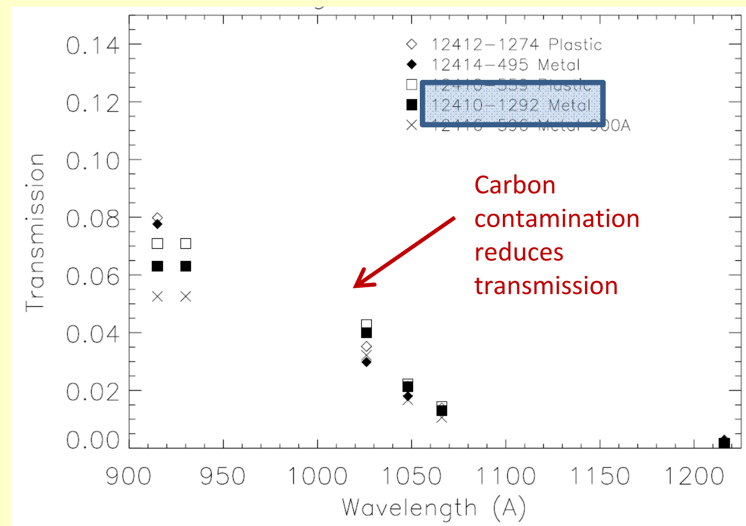
UV Filter Enhancement/Fabrication

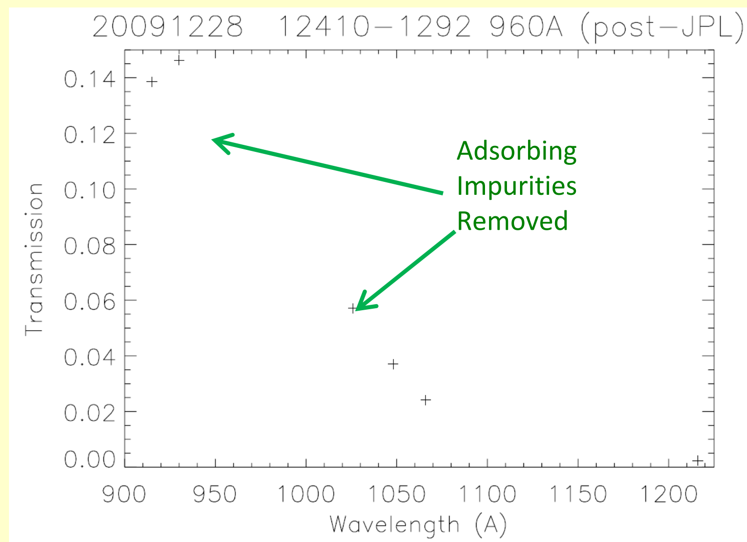
FIRE telescope





Indium foil on Ni mesh





- FIRE Telescope objective to image the very hottest stars, with no interference from Lyman alpha
  - Thin Indium Foil (0.1microns thick) supported by Ni mesh acts as UV filter cutting off transmission above 1100A
  - Carbon contamination of filters significantly degraded performance
  - Filter design does not lend itself to traditional cleaning
- JPL post treatments yielded significant (>2X) improvement in filter transmission
  - Gentle, low-temperature process results in no degradation in kill ratio for Lyman-alpha
    - Indium filter integrity maintained
- ALD AR coating results demonstrate the feasibility of integrated UV filters directly on the detector itself

UV Optical Coatings

- Reflective coatings determine the mission architecture for any UV mission (FUSE, HST/COS, etc)
- FUV has a significant number of spectral lines that are of great interest to astronomers
- Aluminum mirrors require protective coatings (*i.e.* LiF or thick MgF_2) to prevent oxidation which would otherwise destroy reflectivity in the FUV
- These coatings currently necessitate compromises on several levels
  - Polarization issues in Optical
  - Low efficiency in UV forces telescope designs with larger mirrors and separated into LiF and MgF_2 channels to achieve desired sensitivity
- By using very thin, but high quality, MgF_2, both issues can be addressed simultaneously.
  - Very thin coatings minimize impact on polarization of incident light
  - Thin films of MgF_2 (1-2nm) enable higher reflectivity (due to lower absorption losses) than LiF or thick MgF_2
- Table below demonstrates some of the changes that FUSE would have had with better coatings

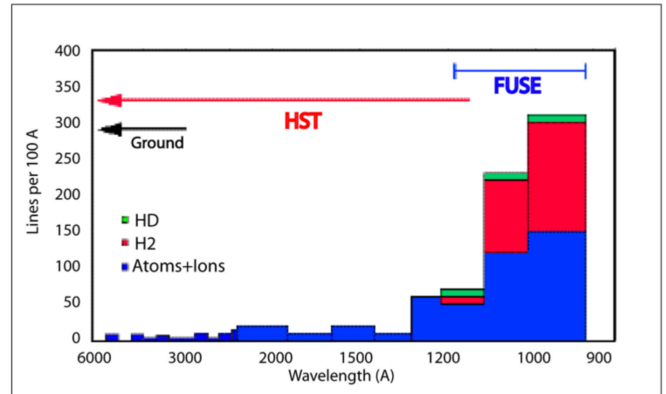
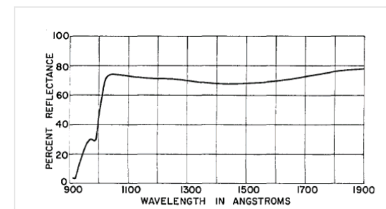


Figure 1, Density of spectral lines by wavelength (adapted from http://fuse.pha.jhu.edu/educ/hill_697_sci.html)



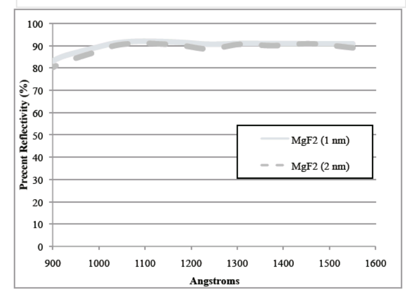
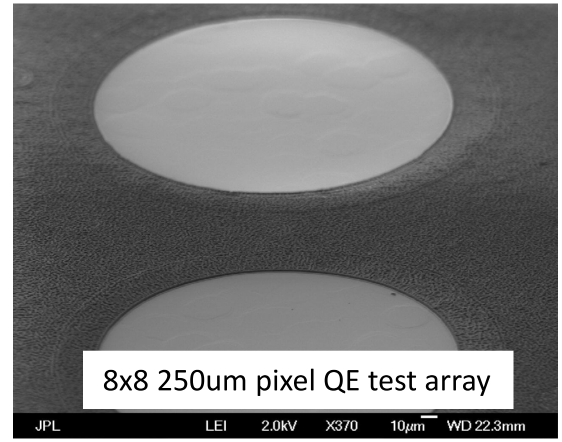


Figure 3, Hunter 1971 (17 nm) LiF/Al compared to the predicted reflectance of Al with 1 and 2 nm thickness MgF_2 (CRC, Henke et al. 1993)

	Resolution	Aeff	Imaging?	Environmental	Size
FUSE	~20,000	~30 cm^2/channel from 1000 – 1180 ~10 cm^2/channel from 900 - 1000	No.	Hygroscopic Coatings	~6 m
FUSE w/ improved coatings	>40,000	Simpler optical design @ 100 cm^2 From 900 - 1180 Angstroms	Yes.	Not hygroscopic	~3 m

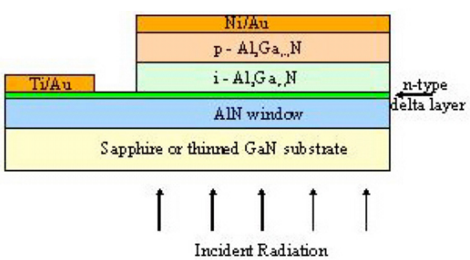
ALD for III-N Detectors

- III-N APD detectors are also useful for UV detection
  - Inherently solar blind to prevent unintended response to visible light
  - Gain factors of 100 or more reported
- High bias required for enhanced gain factors
- Current detectors limited by dark current, but surface passivation (*i.e.* ALD) can be utilized to improve signal to noise

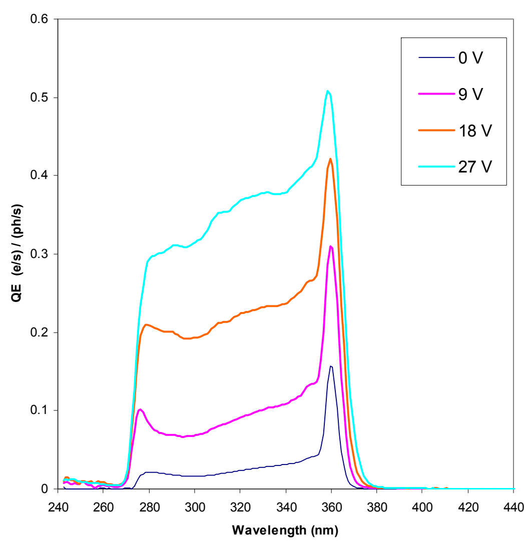


8x8 250um pixel QE test array

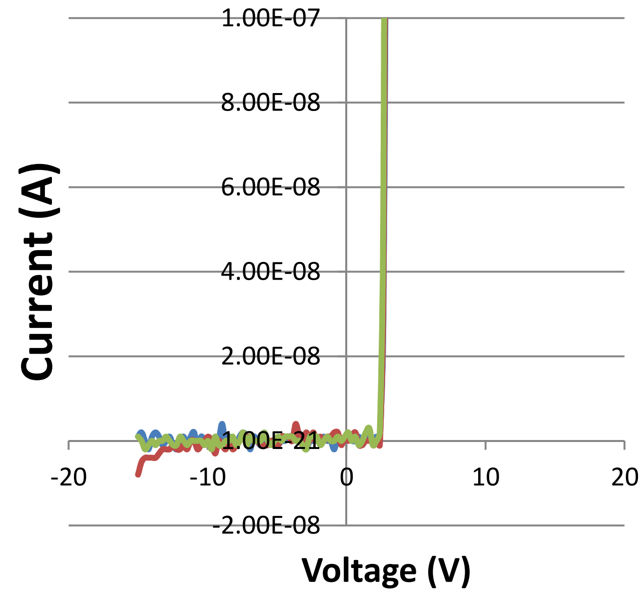
III-N Mesa Structure



QE for different biases



Leakage currents for 250um pixels



Conclusions

- Benefits of ALD for UV instruments and application
  - Ultrathin, highly conformal, and uniform films over arbitrarily large surface area
  - High quality films (density, roughness, conductivity, *etc.*)
  - Angstrom level control of stochiometry, interfaces, and surface properties
    - Multilayer nanolaminates/nanocomposites
    - Low temperature surface engineering
- UV flight applications enabled by ALD
  - Anti-reflective coatings/Mirrors/Filters/Optics for UV/Vis/NIR Detectors
  - Surface Passivation for III-N detectors

JPL
Jet Propulsion Laboratory
California Institute of Technology

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- UV Filters/Mirrors
  - M. Beasley, B. Gantner (U. Colorado CASA)
- III-N Detectors
  - Doug Bell (JPL) and S. Shahedipour, et al (SUNY-Albany CNSE)
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